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TECHNICAL REPORT ARBRL-TR-02276

AN EXPERIMENTAL INVESTIGATION OF
COMPOSITION-B IGNITION UNDER
ARTILLERY SETBACK CONDITIONS (U)

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December 1980



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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by the evacuation of the gap. We, also, found that air leakage, convergent airflow, and the state of the explosive surface influence sensitivity. Further, lower sensitivity is observed with voids internal to the explosive sample rather than with base gaps of similar dimensions. Carefully conducted planar gap tests show that precise ignition thresholds can be defined, and that TNT is somewhat more sensitive than comp-B. We observed that frictional ignitions were produced only when high-melting-point grit was present at the sliding surface.

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I. INTRODUCTION

Some composition-B (comp-B) loaded artillery ammunition has a service premature rate considerably higher than the acceptable level of one per million firings. As a result, the future use of comp-B as a filler for these projectiles is jeopardized. The use of TNT as an alternate fill results in a performance degradation which significantly reduces the effectiveness of these items. It is clear, therefore, that improvements in the comp-B loaded systems would be of genuine benefit. Efforts to obtain these improvements have repeatedly met with difficulties arising from a lack of understanding of the mechanisms which lead to the ignition of the explosive fill during the launch of a projectile. Without this understanding, it is impossible to assess the effectiveness of design and formulation changes proposed to improve the premature rate. There exists, therefore, a need to identify ignition mechanisms and to determine how they are affected by parameters which characterize the projectile at the time of launch.

It is widely accepted that the causes of prematures are many. The a priori possibilities include compression of the explosive, heating of air trapped adjacent to the explosive by rapid compression, frictional heating arising from rotation of the fill with respect to the casing, as well as fuse and propellant malfunction. This is by no means an exhaustive list. Of particular interest are those mechanisms that involve defects in the explosive fill such as base separations, voids, and cracks. The response of an explosive system to a given level of any form of stimulus is usually characterized by the number of ignitions observed for the total number of tests made at that level. For example, the relative safety of fielded ammunition is characterized by an observed rate of occurrence of in-bore premature explosions; also, explosive samples subjected to drop testing are characterized by the drop height required to yield ignition for fifty percent of the samples tested. The statistical nature of this data does not arise because of some inherent indeterminacy in the explosive response, but because of unknown variations in the launch environment and the initial state of the fill, in the case of projectiles, and poor control of the test conditions and the initial state of the sample, in the case of sensitivity testing.

There are alternative philosophies for the study of the premature problem. One approach purposes to provide a prediction of the premature rate for any proposed ammunition system. This requires that as many launch parameters as possible be duplicated by the simulating apparatus. As a consequence, a full-scale or near full-scale device is required and operating costs approach those of actual gun firings. (In some cases, actual gun firings are used for this purpose). Since one cannot hope to observe a rate of one premature per million firings during the course of an experimental program, it is necessary to make the test conditions more severe than the actual launch environment (usually by increasing the pressure) in order to obtain an observable rate of ignition. There exist no reliable procedures for extrapolating statistical data obtained

at severe test conditions back to conditions encountered by ammunition in the field, and no meaningful premature rate prediction can result from this approach. Another point of view discards the notion of premature rate prediction but maintains that standards for maximum allowable defects may be obtained using an apparatus which reproduces as many significant aspects of the launch environment as possible. However, no such apparatus without serious drawbacks has yet been introduced. Since ignition mechanisms are not isolated in this approach, it is difficult to show that a given ignition occurs because of the presence of the defect rather than as a result of an artifact of the apparatus. It is our position at the Ballistic Research Laboratory that, since there exists no single cause of artillery prematures, identifying ignition mechanisms and devising appropriate procedures for studying each independently of the others represents a more fruitful approach.

Previous work in this area includes studies conducted at Picatinny Arsenal using an apparatus referred to as the activator, which simulates the launch pressure environment.¹ Although these results have been used to establish acceptance criteria for base separations in artillery projectiles, more recent findings² render the data suspect by identifying a spurious ignition mechanism. With this problem corrected, the activator has been used in the present investigation to develop some limits of explosive sensitivity for three possible sources of premature ignition. The first of these is the compression of a sound explosive charge. The second source is the heating of air trapped adjacent to the explosive by rapid compression. The third is frictional heating.

II. DYNAMICS OF THE ACTIVATOR

A. Description of the Activator

The activator was originally designed at Picatinny Arsenal as a laboratory-scale artillery setback simulator. Its purpose was to allow extensive testing of various explosives in the setback environment without the great expense of full-scale gun firings. We examined the mode of ignition in the activator as it had been used up to that

¹Schimmel, R. T., "Setback Sensitivity of Composition B Under Conditions Simulating Base Separation in Artillery Projectiles", Picatinny Arsenal Technical Report 3857, 1969 (AD 848-944).

²Taylor, B. C. and Ervin, L. H., "Mode of Ignition in the Picatinny Arsenal Activator", *Proceedings of the Conference on the Standardization of Safety and Performance Tests for Energetic Materials*, Vol 1, 1977, pp. 481-494.

time and found that there was an unsuspected source of frictional ignition which renders most of the old data questionable.² However, this spurious ignition source was easily eliminated and did not arise during the testing reported herein. We find that the redesigned activator is a versatile, useful machine which can be adapted to test various explosives to many sources of ignition that may occur in the artillery launch environment. It should be noted that activator testing requires less explosive and is significantly less costly than most other approaches.

The activator, illustrated schematically in Figure 1, is a device which subjects small explosive samples to the same pressure history that the explosive in an artillery projectile experiences during the gun-launch cycle. It consists of a mild-steel, heavy-confinement cylinder enclosing the explosive sample and hardened-steel driving and backup pistons. The driving piston is activated by a larger piston, which is in turn driven by a propellant burned in the breech. The large piston is usually held in place using shear pins and the breech is instrumented with a pressure transducer. The backup piston rests against a rigid stop which incorporates an adjustment screw to accommodate test fixtures of different lengths and to allow easy installation. The dimensions and masses of the various components are summarized in Table I. Note that buffers and gaps may also be included in the system.

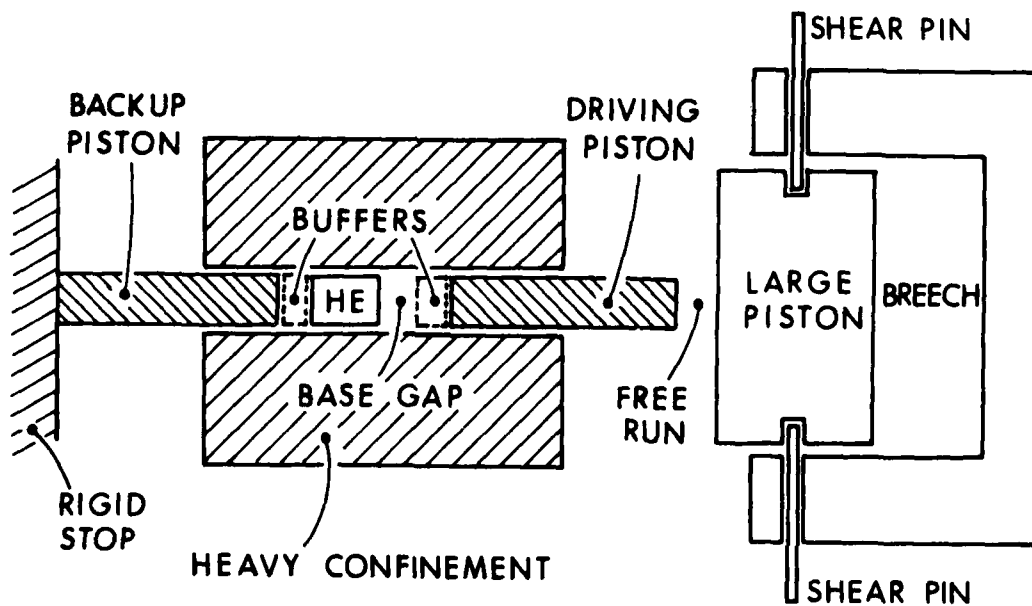


Figure 1. Activator Schematic

TABLE I. Activator Components

Component	Diameter (mm)	Length (mm)	Mass
Confinement	63.5	63.5	-
Bore Hole	12.7	63.5	-
Driving Piston	12.7	54.0	53.5g
Explosive	12.7	12.7	-
Backup Piston	12.7	54.0	53.5g
Large Piston	76.2	-	1.70kg

B. Piston Motion

Two modes of operation are available for the activator. In the contact mode, the explosive and the driving piston, as well as the driving piston and the large piston, are in direct contact. The pressure pulse delivered to the surface of the explosive sample is that developed in the breech amplified by a factor of 36, which is the ratio of the area of the large piston to that of the driving piston. The propellant charge is, therefore, designed to develop a pulse of the same shape as that occurring during the launch of a projectile but of smaller amplitude. This allows the pressure in the activator's combustion chamber to remain low enough to minimize sealing problems.

In the impact mode, there is a base gap between the explosive and the driving piston, a free run gap between the driving piston and the large piston, or both. The sum of the free run, δ_F , and the base gap thickness, δ_G , is referred to as the total run, δ_T . In this case, the

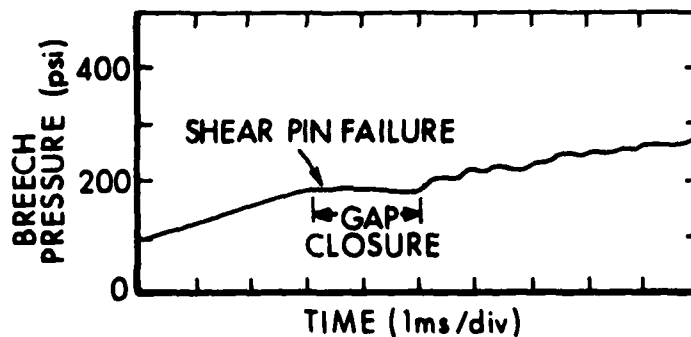


Figure 2. Breech Pressure

pressure at the sample rises more rapidly to a higher peak. When the propellant is ignited, the breech pressurizes until the shear pins fail. With the activator in the impact mode, the large piston accelerates under approximately constant force through the free run, impacts the driving piston, and closes the base gap. This is illustrated in the breech pressure record of Figure 2 (the oscilloscope is calibrated in psi). Bouncing may occur after the impact with the sample. The impact momentum of the piston may be determined as a function of total run and shear pin failure pressure, p_f . This is given by

$$MV = D\left(\frac{\pi}{2} M \delta_T p_f\right)^{\frac{1}{2}}$$

With the values from Table I, this becomes

$$MV = 4 \times 10^{-3} (\delta_T p_f)^{\frac{1}{2}}$$

where δ_T is in mm, p_f is in Pa and MV is in kg-m/s.

C. Pressurization

In the contact mode any force applied to the large piston is transmitted directly to the explosive sample, and the pressure history at the sample surface is exactly the same as that measured in the low-pressure chamber except for the factor of 36. A propellant charge design which yielded a 5-ms rise time was chosen. In the impact mode, the major factor opposing the breech pressure is the inertia of the pistons, rather than the air pressure in the gap, which is quite small until the gap is almost completely closed and the pistons almost completely

stopped. The momentum developed by the pistons is transformed to an impulse delivered to the explosive sample. The precise shape of the pressure wave depends on the mechanical properties of the compressing column and may not be inferred from the momentum. Consequently, one cannot use the breech record to estimate the pressure on the sample. In order to obtain a calibration of the activator, the pressure was measured using a manganin foil gage placed behind the explosive sample. The test configuration is shown in Figure 3. For most of these firings, the total run consisted entirely of free run. No base gap was permitted in order to prevent ignitions, which destroy the gage. One shot was fired with a 1.59-mm (.0625-in.) base gap for which ignition did not occur. A typical pressure record is illustrated in Figure 4. Here the bouncing is evident. The pressurization rate is very nearly constant on the rising portion of the initial pulse. From each such record, it is possible to obtain a peak pressure and pressurization rate. These are plotted versus piston impact momentum in Figure 5. In addition, nominal values of impact momentum, impact velocity, peak pressure, and pressurization rate are summarized in Table II as functions of total run for a nominal shear-pin failure pressure of 2.5 MPa. This may be used as a reference. It should be noted that this calibration was made without use of any buffers and is applicable only to that configuration. Further, pressure measured at the rear of the sample differs from that at the front because of friction between the explosive and the confinement cylinder. No attempt was made to correct for this effect.

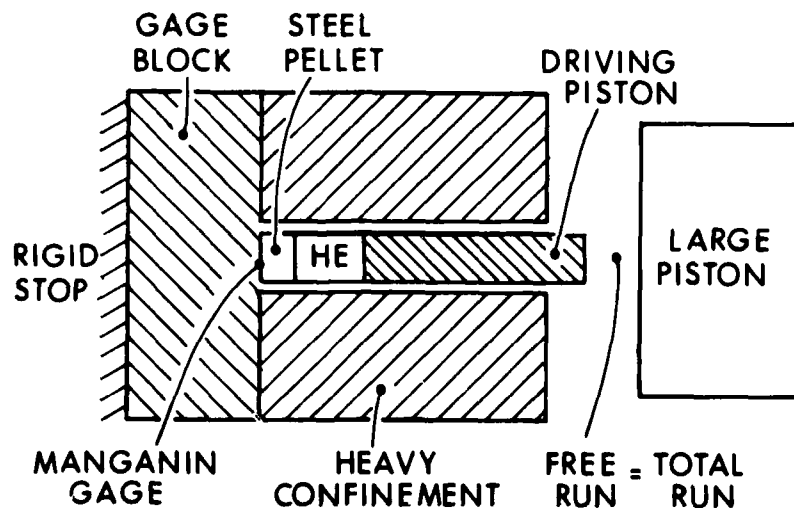


Figure 3. Pressure Measurement Configuration

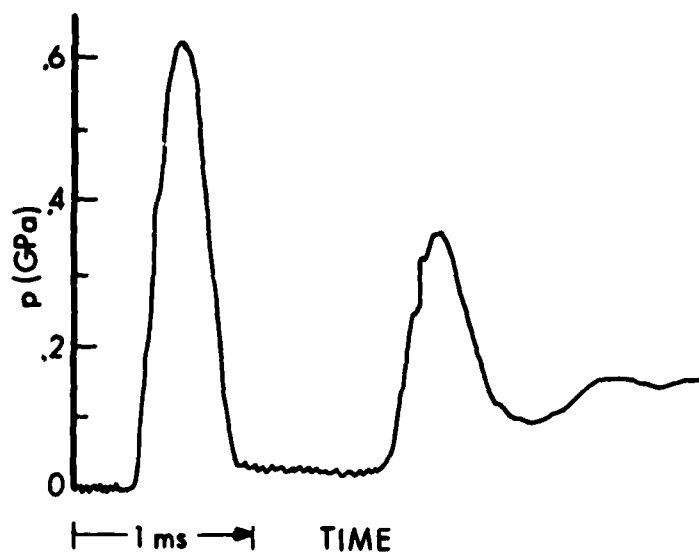


Figure 4. Pressure at Explosive Sample

Table II. Activator Calibration

$p_f = 2.5 \text{ MPa}$				
Total Run δ_T (mm)	Impact Momentum MV (kg-m/s)	Impact Velocity V (m/s)	Peak Pressure p_m (GPa)	Pressurization Rate dp/dt (GPa/ms)
1.59	8.0	4.6	0.18	0.8
3.18	11.3	6.5	0.40	2.0
4.76	13.8	7.9	0.57	3.0
6.35	15.9	9.1	0.72	3.8
9.53	19.3	11.0	0.95	5.1
12.70	22.5	12.9	1.17	6.3
15.88	25.2	14.4	1.36	7.3
19.05	27.6	15.8	1.52	8.2
22.23	29.8	17.0	1.67	9.1

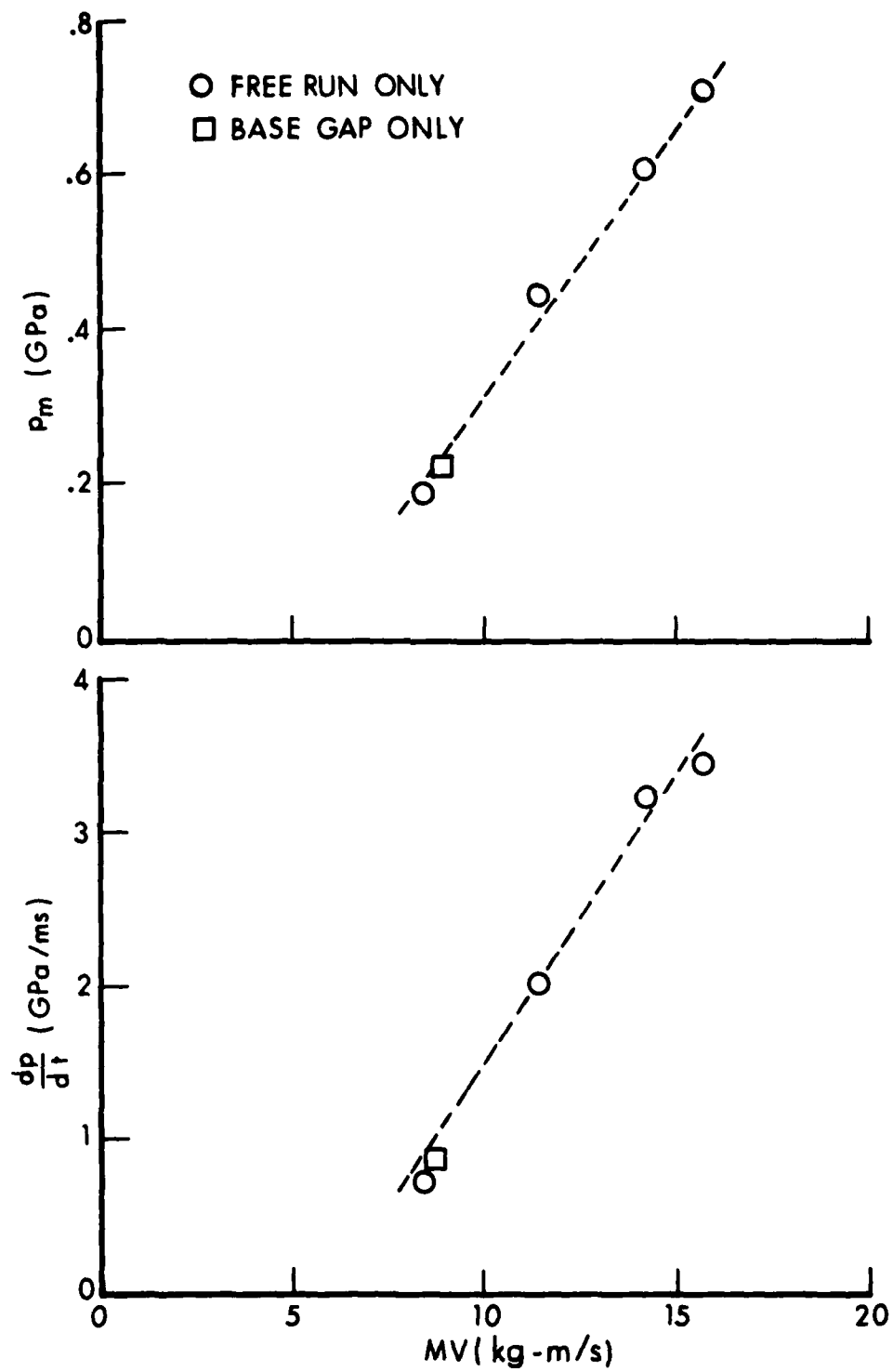


Figure 5. Activator Calibration

D. Sample Preparation

The explosive samples are of two types. The vast majority of those used in the presently reported tests were prepared by casting a long, 12.7-mm (.5-in) diameter cylinder of comp-B. This was then cut into appropriate lengths and each section was finished to the proper size (12.7 mm) and smoothness by polishing on 600 grit paper. When as-cast samples are desired, short 12.7-mm diameter cylinders are cast with one end against a polished plate. These are then finished to size by cutting and polishing at the opposite end. All samples are inspected radiographically to insure the absence of internal voids.

III. IGNITION MECHANISMS

A. Ignition By Compression

1. Background.

During the process of launching a projectile from a gun tube, the high-explosive fill can be subjected to the action of pressure waves from at least three different sources. Because of the steel casing, the explosive is not acted on directly by the breech pressure. However, this acts to accelerate the projectile through the gun tube, and the inertia of the fill creates a stress field within the explosive during launch. It is assumed that the setback pressure history is the same as that in the chamber at the base of the shell and has a rise time of about 3 to 5 ms. When a gap exists between the explosive fill and the base of the projectile, and when the explosive adheres to the casing wall until the acceleration reaches a critical value and then breaks loose, it is impacted sharply by the projectile base. The peak pressure and pressurization rate of the resultant impact wave are dependent on the dimensions and mechanical properties of the projectile, but both are greater than the setback values. The third source is the erratic burning of the propellant charge. In extreme cases, the pressure excursion above normal is sufficient to rupture the gun breech.

There has been concern for a long time about the effect of setback pressure alone on a sound explosive charge as distinct from one containing appreciable voids or flaws. Such defects are unavoidable in production ammunition, but it is necessary to establish whether there exists an upper limit on the performance improvement to be achieved by improving the condition of the explosive fill. The earlier activator tests conducted at 60°C indicated that 92 percent of the samples tested ignited at 0.86 GPa (8.6 kbar, 124 kpsi) while only 16 percent ignited

at 0.65 GPa (6.5 kbar, 94 kpsi)¹. We have shown² that these ignitions were primarily caused by accidental friction effects and are not related to compression alone. Gun firings were also made using 105 mm projectiles modified by the placement of a lead slug above the explosive charge in order to increase the setback pressure.³ These tests indicated that ignition was obtained above about 0.17 GPa (1.7 kbar, 25 kpsi) but the results are questionable because the explosive was not protected from the action of the lead slug. Tests conducted with another device, the NSWC premature simulator, indicate that ignition does not occur in the absence of a base separation at pressures up to 0.42 GPa (4.2 kbar, 61 kpsi).^{4,5}

There are two experimental facts that are firmly established. First, Bridgman⁶ showed that explosive could be isothermally compressed to 5 GPa (50 kbar, 735 kpsi) without ignition. Thus, slow compression to extremely high pressure (small $\frac{dp}{dt}$) will not cause ignition of explosive. Second, Liddiard⁷ showed that shock compression (<0.1 μ s rise time) of pressed comp-B would cause ignition at the 0.40 GPa (4.0 kbar, 58 kpsi) pressure level ($\frac{dp}{dt} > 4 \text{ GPa}/\mu\text{s}$). This establishes that the pressurization rate is a controlling element in the ignition of explosives by pressure waves.

2. Results.

Sound (not perfect) comp-B castings were tested in the activator. A nominal pressurization rate of 0.15 GPa/ms is obtained in the contact mode with the largest propellant charge used. In the impact mode, the pressurization rate of the initial pulse can be increased to 3 GPa/ms and higher. Results for both types of pressure history are reported

³Comp-B Improvement PIP No. 1-77-09-7629, *Semiannual Technical Review for U.S. Army Armament Materiel Readiness Command*, November, 1978.

⁴DeVost, V.F., "Premature Simulator (Final Progress Report)", *Naval Ordnance Laboratory Technical Report 74-178*, October 1, 1974.

⁵Hershkowitz, J., *Personal Communication*, October 16, 1979.

⁶Bridgman, P.W., "The Effect of High Mechanical Stress on Certain Solid Explosives", *Jour. Chem. Phys.*, Vol 15, 1974, pp. 311-313.

⁷Liddiard, T.P., "The Initiation of Burning in High Explosives by Shock Waves", *Fourth Symposium on Detonation*, October 1965, pp.487-498.

in Table III. In the contact mode, which simulates normal setback, no ignition was obtained in 10 shots (0/10) to a peak pressure of 0.74 GPa (7.4 kbar, 107 kpsi). In impact tests, with much higher pressurization rates, a number of shots were fired. The peak pressure and pressurization rate were increased to 1.67 GPa (16.7 kbar, 242 kpsi) and 9.1 GPa/ms, respectively, without yielding ignition.

Table III. Compression Ignition Statistics

Free Run, δ_F	Peak Pressure p_m	Pressurization Rate dp/dt	Ignition Statistics
(mm)	(GPa)	(GPa/ms)	
0	0.74	0.15	0/10
6.35	0.72	3.8	0/12
9.53	0.95	5.1	0/5
12.70	1.17	6.3	0/1
15.88	1.36	7.3	0/1
19.05	1.52	8.2	0/1
22.23	1.67	9.1	0/1

3. Conclusions.

Since ignition did not occur in our tests at pressures and pressurization rates exceeding those in the gun firing³ and original activator¹ tests, it may be concluded that the ignitions in the latter tests were not due to compression alone. It appears that a soundly cast comp-B charge will be safe when exposed to setback and impact compressions well above any levels presently considered for weapons systems. The critical pressurization rate for ignition by compression must lie somewhere between the value of 9.1 GPa/ms established by the present results and the shock wave value.

B. Ignition by Compressive Heating of Air

1. Background

The original activator studies¹ showed that comp-B was further sensitized by the presence of a base gap filled with air. While these results are suspect, another more reliable investigation conducted for Picatinny Arsenal by Arthur D. Little, Inc. gives the same indication.⁸

⁸Arthur D. Little, Inc., "Cavity Standards for Cast Loaded Artillery Projectiles", Revised Final Report for Picatinny Arsenal, March 30, 1957.

In this study, hemispherical and conical cavities in comp-B filled with air at atmospheric pressure were subjected to a pressure pulse created by the action of a drop weight on a piston in an oil-filled cylinder. The following observations from this work are pertinent to the present investigation:

- a. A sufficiently high pressurization rate is required to yield an ignition with a given cavity size.
- b. Higher pressures are required to ignite smaller cavities.
- c. Cavity shape has little effect when comparing hemispherical and conical cavities.
- d. Comp-B is less sensitive to ignition from compression of internal cavities than to ignition from compression of surface cavities.
- e. Sensitivity is affected by the state of the surface including the presence of irregularities.
- f. TNT is more sensitive than comp-B.

Another study using an activator was conducted at the Royal Armament Research and Development Establishment in the United Kingdom.⁹ In these tests the air gap was sealed adjacent to the explosive by means of a dished polyethylene disc and the activator was driven by a falling weight. Pertinent observations from this work include the following:

- a. The size of the air cavity affects sensitivity.
- b. TNT is as sensitive as comp-B.

We shall find it of interest to compare the foregoing with our present results.

Initially, during the course of the compression ignition study, buffer discs of Cerrobend were placed between the steel pistons and the explosive in an attempt to prevent any accidental frictional ignition from occurring. Cerrobend is an alloy with a normal melting point of about 70°C, and was deliberately chosen with the thought that any frictional heating would be limited to this temperature as a maximum. When

⁹Hubbard, P.J., Lee, P.R. and Tisley, D.G., "The Sensitiveness of High Explosives to Impulsive Loads", *Proceedings of the Conference on the Standardization of Safety and Performance Tests for Energetic Materials*, Vol. 1, 1977, pp. 495-507.

such buffer discs were used on the impact shots, the explosive ignited. From this result, we erroneously concluded that cast comp-B was sensitive to impact ignition with a 6.35-mm (.25-in) free run and from that time on, the comp-B was precompressed to approximately 0.25 GPa (2.5 kbar, 36 kpsi) by firing the activator in the contact mode in order to reduce this supposed sensitivity by causing any tiny voids or other imperfections to collapse relatively slowly. It was only considerably later, in the course of friction tests, that we found that Cerrobend buffer discs did get hot enough to ignite comp-B. However, the use of precompressed samples did simplify our experimental setup and led us to discover effects which we might have missed had we used only unprecompressed samples.

Another issue that arose is the leakage of air from the gap while it closes. Air may leak past the explosive sample, past the piston, and possibly into the pores of the explosive itself. If air leakage is an important factor (as it turns out to be) then, it is important to eliminate the first two leakage points in order to have well-controlled, repeatable experiments. Precompression of the sample in its confinement cylinder seems to be sufficient to eliminate leakage past the sample for the short duration of the experiments. Leakage past the piston may be eliminated by using tight shrink-fitted pistons. It is also possible to place a self-sealing gap (one that seals against the explosive when pressurization begins) against the samples such that neither precompression, nor shrink-fitting, are required. Leakage into the surface of the sample is a property of the state of the explosive and should be a subject of study. The hypothesis that this surface effect is present arose because of differences in sensitivity observed between precompressed and unprecompressed samples using self-sealing gaps. In addition, there is a sensitivity difference between cut and polished and as-cast explosive surfaces which may be explained by this theory.

2. Role of Air

A 6.35-mm air gap at the explosive results in fairly reliable ignition of the explosive, giving 10 ignitions in 11 firings (10/11). The most direct method of determining whether these ignitions were due to compressive heating of air is to evacuate the base gap. However, at the time we were interested in performing this test, the vacuum hardware had not been fabricated and machine shop priorities indicated a long delay. Therefore, an interim test was devised. We thought that if the ignition in the air gap tests was not caused by hot gas, then it could only be a result of either impact of the piston assembly against the sample or extrusion of explosive between the piston and cylinder and ignition by contact with frictionally heated steel. Placing the driving piston directly against the sample eliminates any possibility of hot gas ignition by excluding the gas. Allowing a 6.35-mm free run between the driving piston and the large piston allows the large piston to acquire the same momentum as in the air gap test and hence subject the explosive to the same pressure wave and extrusion as in that test. When we did this, there resulted no ignition in 5 tests (0/5). Later, vacuum hardware as shown in Figure 6 was obtained and tests were run using a vacuum

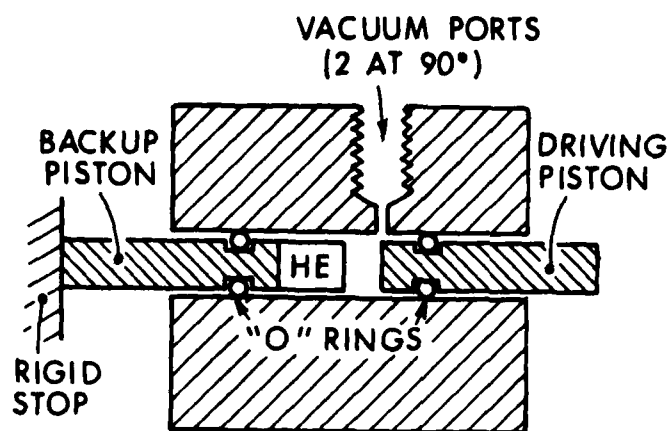


Figure 6. Vacuum Gap Configuration

pump to evacuate the air in the base gap to a pressure of less than 133 Pa (1 mm Hg). In these vacuum tests, no ignition was obtained in 5 trials (0/5). These results, summarized in Table IV, indicate that ignition does not occur unless sufficient air is present in the gap adjacent to the explosive and thus support the interpretation that ignition is caused by compressive heating of air.

Table IV. Effects of Air on Ignition

Base Gap, δ_G (mm)	Free Run, δ_F (mm)	Total Run, δ_T (mm)	Initial Pressure (MPa)	Ignition Statistics
6.35	0	6.35	0.101	10/11
0	6.35	6.35	-	0/5
6.35	0	6.35	vacuum	0/5
1.59	4.76	6.35	0.406	0/1
1.59	4.76	6.35	0.578	1/2
1.59	4.76	6.35	0.811	3/3

A test related to the air gap and vacuum gap tests was performed to get an indication of the importance of the quantity of air in the base gap. For instance, the 6.35-mm air gap may be narrowed by a factor of four to 1.59 mm (.0625 in) and pressurized until the mass of the air is equal to that in the original gap. One can also leave a free run of 4.76 mm (.1875 in) so that the impact momentum applied to the 1.59-mm gap is nearly identical to that on the 6.35-mm air gap for which 10 ignitions in 11 trials were obtained. With an initial pressure of 0.406 MPa (4.0 atm), no ignition was obtained in a single shot (0/1).

This result and those at initial pressures up to 0.811 MPa (8.0 atm) are also summarized in Table IV. Our analysis¹⁰ for finite rate (nonadiabatic) compression also shows that sensitivity increases with the quantity of air in the gap. We may conclude from these results that the quantity of air in the base gap is important to the ignition process. This fact is of value in interpreting the following experiments.

3. Convergence and Air Leakage

Some air compression tests were run using loose fitting polyethylene buffers. At that time, an unexpected effect was revealed which is of major importance as a possible cause of in-bore prematures. In the course of fabricating these buffers, rough blanks were first stamped from a sheet of polyethylene and then were machined to final size on a lathe. The punch which had been used for the stamping had a locating point at its center which impressed a shallow dimple in one side of the blanks during the punch stroke. During our tests, we accidentally found that anomalous ignition occurred when the dimple side of the piston faced the sample. The results are presented in Table V. For a plane parallel gap with a loose-fitting polyethylene piston, no ignitions were obtained in 4 trials (0/4). When the dimple was turned toward the explosive sample with the same total gap, 2 ignitions in 2 trials (2/2) resulted. As the total air gap was reduced, ignitions continued to occur until the gap thickness was less than 1.57 mm (.042 in).

Table V. Effects of Dimple

Base Gap, δ_G (mm)	Depth of Dimple (mm)	Total Gap (mm)	Ignition Statistics
3.18	0	3.18	0/4
2.64	0.54	3.18	1/1
2.46	0.72	3.18	1/1
1.57	1.02	2.59	1/1
0.79	1.22	2.01	0/1
0	1.02	1.02	0/1

These observations may be explained as follows. As the piston approaches the surface of the explosive sample, air flows into the dimple and is ultimately sealed in when the piston contacts the surface. This has two effects. First, the quantity of air per unit explosive

¹⁰Starkenber, J., "Analytical Models for the Compressive Heating Ignition of High Explosives", BRL Technical Report ARBRL-TR-02225, March 1980.

surface area is greater in the dimple than in a planar gap closed from the same initial total-gap thickness. In addition, after the dimple is sealed and pressurization continues, leakage of air away from the ignition site, as occurs with a planar gap, is precluded.

We did not initially consider the importance of leakage, and attributed the sensitization observed to convergent airflow. In order to further study that effect, we selected a test configuration that would result in the maximum possible convergence. This was a hemispherical cavity (bubble) in a soft plastic material (RTV rubber or Dow Corning Sylgard 182) which would collapse uniformly toward its center upon application of pressure. This was placed in contact with the sample as shown in Figure 7 and formed a self-sealing gap. At the time, it was not convenient to cast such bubbles into soft plastic, so, as a substitute, holes were drilled with a standard 120°-included-angle drill bit into frozen buffers with a depth approximately equal to the drill diameter. The results of test using various hole diameters and free runs are presented in Table VI.

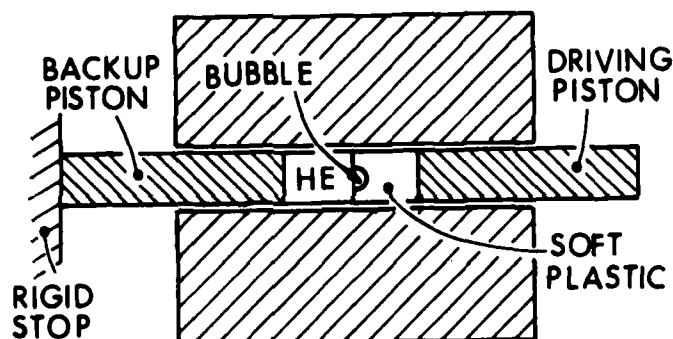


Figure 7. Bubble Test Configuration

Table VI. Ignition Statistics for Bubble Tests on Precompressed Samples

Bubble Size (mm)	Free Run, δ_F (mm)			
	6.35	3.18	1.59	0
3.18	1/1			1/1
1.57	16/18			0/2
1.04	6/7	1/1	0/1	0/2
0.51	4/5	0/1		
0.40	1/1			
0.40x0.18	0/1			
0	0/3			

It was necessary to establish that the ignitions obtained with the bubbles were caused by the trapped air. For this purpose, tests were conducted with the air evacuated from the bubble region as shown in Figure 8. The conditions for the air bubble and vacuum bubble tests were kept as similar as possible. However, some differences could not be avoided. To insure that the air was evacuated from the plastic bubble in the vacuum shots, the plastic was not positioned against the precompressed comp-B as was done for the air bubble shots, but was spaced 1.59 mm from the surface. This represents an overtest for the vacuum shots since the additional base gap should enhance any tendency for the system to ignite. In addition, two slices were removed from the side of the plastic cylinder to insure that a free channel existed between the base gap and each of the vacuum ports. The results are summarized in Table VII. The first group at atmospheric pressure are shots which had been fired prior to the vacuum tests. These indicate that a 1.57-mm air bubble is almost certain to ignite precompressed comp-B when a 6.35-mm total run is used. A precompressed comp-B sample was then tested in vacuum-modified hardware under a vacuum of less than 26.6 Pa (0.2 mm Hg). Since no ignition occurred, the test was repeated until we had performed a total of five shots using the same sample (the plastic bubble was changed before each shot). For the sixth shot with this sample, the plastic was positioned against the sample surface (no base gap) and the shot was fired at atmospheric pressure. In this case, the sample ignited. Another precompressed comp-B sample in vacuum-modified hardware was then subjected to the same series of five vacuum shots with no ignition and then an air shot which resulted in ignition.

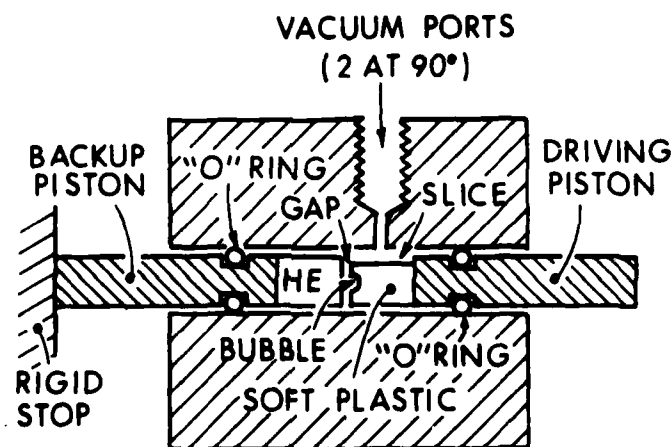


Figure 8. Vacuum Bubble Configuration

Table VII. Comparison of Ignition Statistics for Air and Vacuum Bubble Tests on Precompressed Samples

Initial Pressure (MPa)	Hardware	Base Gap, δ_G (mm)	Free Run, δ_F (mm)	Total Run, δ_T (mm)	Bubble Size (mm)	Ignition Statistics
.101	Standard	0	6.35	6.35	1.57	16/18
.101	Modified	0	3.18	3.18	1.57	2/2
Vacuum	Modified	1.59	1.59	3.18	1.57	0/10

We conclude from these tests that for ignition to occur with a bubble in soft plastic sufficient air must be present. The implication is that explosive ignition is due to heating of the air by rapid compression. It is interesting to note that bubbles of surprisingly small diameter in soft material adjacent to explosives can cause ignitions at relatively modest pressurization rates. A bubble only 0.40 mm (.016 in.) in diameter subjected to a pressurization rate lower than 3.8 GPa/ms is sufficient to ignite comp-B. This has serious implications for artillery ammunition in which a plastic or any easily deformed material is used adjacent to the explosive fill, particularly around base fuses or where setback wads can collapse bubbles against the explosive.

We subsequently realized that convergence was not the only possible cause of the difference in sensitivity observed between planar gaps and bubbles. The diametric clearance between the pistons and the cylinder is approximately 0.025 mm (.001 in) and this allows sufficient leakage of air to affect the ignition sensitivity measurements in a gross manner. If any attempt is made to reduce the clearance, it becomes impossible to fit the pistons into the cylinder. Thus, precise ignition sensitivity measurements in this circumstance are not possible since the air leakage varies depending upon the clearance in each test. An estimate of the leakage rate may be obtained assuming the choked adiabatic flow of an ideal gas.

$$\dot{m} = pA \left(\frac{\gamma}{RT} \right)^{\frac{1}{2}} \left(\frac{2}{\gamma+1} \right)^{(\gamma+1)/2(\gamma-1)}$$

The cross-sectional area, of the opening, A, is approximately $5 \times 10^{-7} \text{ m}^2$. The pressure and temperature may be assumed to be 0.1 GPa and 1500 K, respectively. For air, the ratio of specific heats, γ , is assumed to be 1.4 and R is 287 J/kg-K. This yields

$$\dot{m} \approx 5 \times 10^{-5} \text{ kg/ms}$$

The initial mass of air in a 6.35-mm gap is about 10^{-6} kg . At this flow rate, the entire gap would be evacuated in 20 μs . The actual leakage rates are considerably smaller but this indicates that leakage can be a problem. In order to verify the leakage problem and to establish a test procedure which eliminates it when planar gaps are used, a new

experimental configuration was devised. Tests were conducted using precompressed comp-B samples and sealing the air gap with an oversized polyethylene plug 6.35-mm thick at the face of the driving piston. The polyethylene was cooled in a liquid nitrogen bath to shrink it sufficiently to allow insertion into the confinement cylinder. Since the polyethylene piston is a close fit in the hole even when shrunk, considerable care was taken to avoid trapping excess air between the polyethylene and the sample. The results of these tests are summarized in Table VIII along with similar results for the original steel piston configuration. It should be noted that the pressure and pressurization rate calibration apply to the steel piston configuration and that the values when a layer of polyethylene is present are probably lower. Originally, using steel pistons, a 3.18-mm (.125-in) air gap gave only one ignition in twenty-eight firings (1/28). When the tight-fitting polyethylene pistons were used, six ignitions in six shots (6/6) resulted, even though the stimulus is probably somewhat milder. The question arises, then, as to whether this sensitization is due to sealing against leakage or to the insulating effects of the polyethylene. In order to answer this question, several tests were conducted with a thin (0.1-mm) polyethylene film glued to the face of the steel-driving piston which provided insulation but not sealing. In this case, five ignitions in nine shots, (5/9) were obtained. Thus, it can be concluded that while the insulating effect of polyethylene is important, so is the effect of gas leakage during gap closure, and the question of convergence must be resolved by comparing bubble tests with sealed planar gaps. This is discussed in a subsequent section of this report.

Table VIII. Effects of Sealing and Thermal Insulation

Base Gap, δ_G (mm)	Free Run, δ_F (mm)	Total Run, δ_T (mm)	Piston Material	Sealing	Insulation	Ignition Statistics
3.18	0	3.18	Steel	No	No	1/28
3.18	0	3.18	Tight	Yes	Yes	6/6
3.18	0	3.18	Polyethylene Polyethylene Film	No	Yes	5/9

4. Explosive Surface Effects

In the course of the experimental program, samples were tested in the precompressed and unprecompressed state. When the vacuum bubble shots were being fired, we knew that precompression of the sample was not necessary for desensitization to impact since tests had been completed showing that the unprecompressed comp-B was quite insensitive to impact. A considerable saving of time could be realized if each charge which was tested did not have to be precompressed first. A series of air and vacuum tests was devised in which the unprecompressed comp-B (whose surface had been finished flat by grinding on 600 grit paper) was first tested under vacuum conditions. Since no ignition was expected in the vacuum test,

the same comp-B sample would then be subjected to an air bubble test which was expected to ignite the comp-B and destroy the vacuum hardware which contained the sample. In this way, we felt that air and vacuum tests would be run under identical conditions on the same sample and the confinement hardware could be used for two experiments before being destroyed. All went as expected in that none of the vacuum tests exhibited ignition, while all of the air tests did. However, we then realized that all the conditions were not identical. The vacuum shots were all fired against unprecompressed comp-B and the air shots against precompressed comp-B. An atmospheric test was then made on unprecompressed comp-B yielding no ignition. When the same explosive sample (which was then precompressed by virtue of the first test) was retested with another air bubble of the same size, ignition occurred. Test results for various size air bubbles in soft plastic are contained in Table IX. No definitive tests have been made to verify the hypothesis, but we believe that one effect that precompressing the explosive sample could have would be to seal any microcracks or fissures extending from the surface into the sample and prevent air from leaking into the available volume within the casting. This would result in lower peak air temperature since the minimum volume is greater at the same pressure. It would, also, present greater explosive surface area to the air as it compresses and allow more heat to be conducted away thus further lowering the interface temperature.

Table IX. Comparison of Precompressed and Unprecompressed Samples

Bubble Size (mm)	$\delta_F = 6.35$ mm		$\delta_F = 3.18$ mm	
	Precompressed	Unprecompressed	Precompressed	Unprecompressed
3.18	1/1	1/1		
1.57	16/18	0/1		0/4
1.04	6/7	0/1	1/1	
0.51	4/5	0/1	0/1	
0.40	1/1	0/1		
0.40x0.18	0/1			
0	0/3			

These results apply to unprecompressed comp-B samples whose surfaces had been mechanically finished flat by grinding on 600 grit sand paper. We did not know if the same effect would appear with as-cast surfaces. Consequently, we ran a series of tests with bubbles against as-cast surfaces of comp-B. The results are shown in Table X. It is apparent that the as-cast surfaces have different properties than surfaces which are finished flat by grinding. Specifically, they seem to be more sensitive than polished surfaces, unless the latter have been precompressed. Microscopic examination of the explosive shows that unprecompressed cut and polished surfaces exhibit defects where RDX particles have apparently been torn out. These defects sometimes expose more RDX. Flat polished RDX always appears at this kind of sur-

face. Precompression of the sample does not eliminate these defects nor does it increase the density of the sample. As-cast surfaces exhibit defects where minute pieces of TNT have adhered to the bottom casting plate. These defects almost always expose RDX. It is possible that the exposure of RDX particles in defects where convergent airflow occurs represents a more sensitive situation than TNT-lined microcavities with RDX exposed only on the flat surfaces, although we shall present some evidence to show that TNT is not less sensitive than RDX to this type of ignition. Another explanation for the observed differences in sensitivity is that air leaks away through the surfaces of cut and polished unprecompressed samples rendering them less sensitive than their precompressed counterparts and as-cast samples which permit less leakage.

Table X. Comparison of Polished and As Cast Surfaces

$$\delta_F = 6.35 \text{ mm}$$

Bubble Size (mm)	Precompressed		Unprecompressed	
	Cut and Polished		Cut and Polished	As-Cast
3.18	1/1		1/1	5/5
1.57	16/18		0/1	3/4
1.04	6/7		0/1	1/5
0.51	4/5		0/1	
0.40	1/1		0/1	
0.40x0.18	0/1			
0	0/3			

5. Voids in Explosive

Tests which have been performed on comp-B samples containing both natural and artificial voids are listed individually in Table XI. Hemispherical cavities were drilled in the flat ends of 6.35-mm long charges and then two charges were butted together to form a spherical internal cavity. When cavities of 3.17-mm and 4.76-mm diameter were tested with a free run of 3.18 mm, no ignition occurred in either shot. Three more shots were fired with the hemispheres at the surface of the charge and none of these ignited. Natural cavities were then tested with 12.7-mm free run. These cavities were measured using the radiographs of the charges (one view only) and vary considerably in size, (from 0.5-mm to 2.0-mm diameter for voids and up to 4.0-mm diameter for mixed porosity). In order to obtain ignitions, the cavity must be fairly large compared to defects which are acceptable under radiographic inspection criteria for artillery ammunition. In fact, the two cases in which ignitions occurred had multiple voids.

Table XI. Voids in Explosive

Description of Cavity	Number of Cavities	Cavity Diameter (mm)	Free Run (mm)	Ignition
Artificial Sphere (Internal)	1	3.18	3.18	No
Artificial Sphere (Internal)	1	4.76	3.18	No
Artificial Hemisphere (Surface)	1	4.76	3.18	No
Artificial Hemisphere (Surface)	1	4.76	3.18	No
Artificial Hemisphere (Surface)	1	4.76	3.18	No
Natural (Internal)	5	0.75	12.7	Yes
		1.0		
		1.0		
		1.25		
		2.0		
Natural (Internal)	1	1.0	12.7	No
Natural (Internal)*	2	1.25	12.7	No
		1.50		
Natural (Internal)	1	1.0	12.7	No
Natural (Internal)	4	0.5	12.7	Yes
		0.75		
		1.25		
		2.0		
Natural (Internal)*	1	4.0	12.7	No

*Diffuse region of mixed solids and voids.

6. Sealed Planar Gap Test

With the experience gained during the testing, it was possible to design an experiment to determine the planar gap ignition thresholds of comp-B and TNT. Specifically, we wanted to determine the piston impact momentum required to ignite each explosive as a function of base gap thickness. We chose to consider as-cast surfaces. In order to eliminate leakage, shrink-fitted polyethylene pistons were used and the samples were precompressed. Our previous work shows that cut and polished comp-B surfaces are sensitized by precompression but the effect on as-cast surfaces is unknown. The ignition statistics for comp-B tests conducted with base gaps of 1.27 mm and 1.52 mm are presented in Table XII.

Table XII. Sealed Planar Gap Ignition Thresholds for Comp-B

Free Run, δ_F (mm)	Total Run, δ_T (mm)	Ignition Statistics	
		$\delta_G = 1.27 \text{ mm}$	$\delta_G = 1.52 \text{ mm}$
0	1.52		0/1
1.59	3.11		1/1
3.18	4.45	0/1	
6.35	7.62	2/5	
7.94	9.21	6/9	
9.53	10.80	2/2	

These results are compared with those from the bubble tests in Table XIII. It appears that the bubble configuration leads to greater sensitivity but it must be remembered that the pressurization rate is not identical in the two configurations. We may tentatively conclude that there is a convergence effect.

Table XIII. Comparison of Planar Gap and Bubble Tests

Total Run, δ_T (mm)	Comparison	
	Planar Gap $\delta_G = 1.27 \text{ mm}$	Bubble $d = 1.04 \text{ mm}$
0		0/2
1.59		0/1
3.18		1/1
4.45	0/1	
6.35		6/7
7.62	2/5	
9.21	6/9	
10.80	2/2	

The statistical nature of data presented in this form is nicely exhibited by the ignition threshold for a base gap of 1.27 mm. It appears to smear out between total runs of 4.45 mm and 10.80 mm with a fifty-percent point in the vicinity of $\delta_T = 8 \text{ mm}$. Thus, there appears to be a good deal of indeterminacy in the experiment. This arises because there does not exist a repeatable one-to-one correspondence between the total run and the actual stimulus (pressurization rate) delivered to the explosive sample. There is a shot-to-shot variation in the piston impact momentum caused by the variation in shear pin failure pressure and a further variation in resulting pressurization caused by variations in the mechanical properties of the compressing column. Data is available which allows us to eliminate the former since the shear-pin failure pressure may be determined from the breech-

pressure record and the impact momentum computed. Each firing may then be entered on a plot of impact momentum versus base gap thickness using unique symbols for ignition and non-ignition as in Figure 9. In this case, the ignition thresholds may be defined very precisely. There is very little overlap near the threshold. One anomalous ignition of comp-B has been identified and is marked by an arrow in the figure. The results indicate that TNT is more sensitive to compressive heating ignition than comp-B.

7. Conclusions

As in reference 8, we have found that a sufficiently high pressurization rate is required to cause an ignition with a given base gap thickness or bubble diameter and that sensitivity is strongly affected by the amount of air in the cavity. In addition, we have established that air is required for ignition. We, also, agree that comp-B is less sensitive to ignition from compression of internal voids than to ignition from compression of surface cavities and that the state of the explosive surface affects sensitivity. On the other hand, we have observed that there is an apparent effect of cavity shape when comparing planar and convergent gaps. The observation that TNT is more sensitive than comp-B is somewhat difficult to resolve with the fact that TNT is a component of comp-B. This result may be in keeping with the observed effects of the state of the explosive surface if comp-B presents a more porous surface than TNT. Use of impact momentum as the parameter characterizing the stimulus leads to more consistent results than use of the total run since the former also includes the effect of shear pin failure pressure, which varies somewhat from test to test. Adequate control is often difficult or impossible to obtain. However, we have seen that care in preparation of samples and setup of experiments narrows the region of indeterminacy.

C. Ignition By Friction

1. Background

The primary reason that friction tests were undertaken using the activator at BRL was to shed light on an in-bore premature that occurred while firing the 8-inch XM650 RAP projectile at -10°C at Yuma Proving Ground on 26 January 1976. Radiographs of the projectile prior to firing taken at 90° angles were available and close examination of these revealed no obvious flaws in the explosive fill that might account for this premature. Since the firing was cold, the comp-B load had shrunk with respect to the steel case and was approximately 1.93 mm (.076 in.) shorter and 0.38 mm (.015 in.) smaller in diameter than the steel case even though no gaps existed at room temperature. This shrinkage had two effects. First, there was a total longitudinal air space 1.93-mm thick and a total transverse air space 0.38-mm thick between the explosive and the case. If the explosive charge were to move as a one-piece piston and in

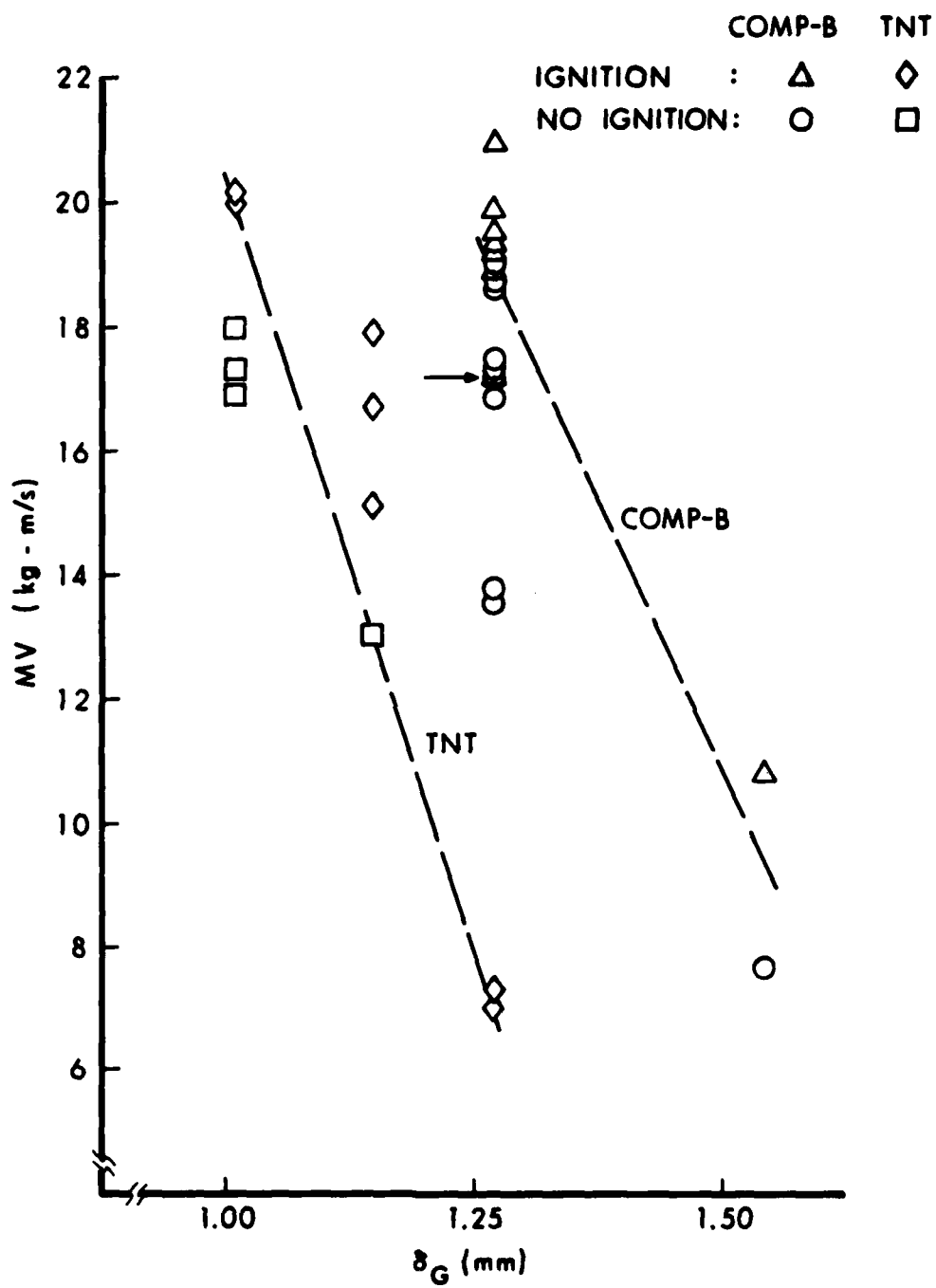


Figure 9. Ignition Thresholds for Comp-B and TNT

such a manner that air was tightly trapped and then heated by rapid compression, it is conceivable that ignition could occur. The second effect is that upon shrinking; the cylinder of explosive comes free of the shell walls and consequently may rotate with respect to the casing during the spin-up phase of launch. Tests covered by flash radiographs at Aberdeen Proving Ground showed 57° relative rotation of one out of four XM650 RAP projectiles fired at -51°C.¹¹ Such rotation occurs at a rapid rate (approximately 30 m/s) and peak setback pressure acts simultaneously as a normal load on the sliding surface. The maximum temperature of the explosive is limited by its melting point when it slides over a steel surface. However, if there is high melting point grit at the sliding interface, the maximum temperature is limited by the melting point of the grit if there is a sufficient amount present for the particles to slide over one another. Bowden et al. have studied this phenomenon extensively and their work is summarized in reference 12. Dyer and Taylor¹³ have studied frictional ignition of explosives caused by grit sliding at controlled velocity and controlled pressure. As a result of the XM650 premature investigation, it became apparent that the primer paint itself was a source of grit. According to the MIL-SPECS for this item, 50 to 55 percent of the weight of solids in this paint is required to be iron oxide (Fe₂O₃), which has a melting point of 1565°C. Furthermore, according to these specifications, 0.5 percent of this iron oxide can be composed of particles larger than 44 microns. With this information available, we decided to use the activator to conduct high-velocity, high-pressure friction tests of comp-B against primer paint films and other materials.

2. Activator Friction Test

The activator configuration used for friction tests is shown in Figure 10. The inner surface of the steel confinement is used as the test friction surface. It can be left as smooth steel, grooved (threaded), pickled in acid to roughen the surface, or roughened and painted. The explosive sample is separated from the steel pistons by two inert buffer discs. The purpose of these is to isolate the explosive from any hot spots that may be formed as the steel pistons slide

¹¹Aberdeen Proving Ground Firing Record No. P-82543, TECOM Project No. 2-MU-003-650-200, "Malfunction Investigation of 8-Inch, HE, Rocket-Assisted Projectile (RAP), XM650E4", Zelik, H. J., Test Director, 14 July 1976.

¹²Bowden, F. P. and Yoffe, A. D., *Initiation and Growth of Explosion in Liquids and Solids*, London, Cambridge University Press, 1952, pp. 12-27, 63-66.

¹³Dyer, A. S. and Taylor, J. W., "Initiation of Detonation by Friction on a High Explosive Charge", *Fifth Symposium (International) on Detonation*, August 1970, pp. 291-300.

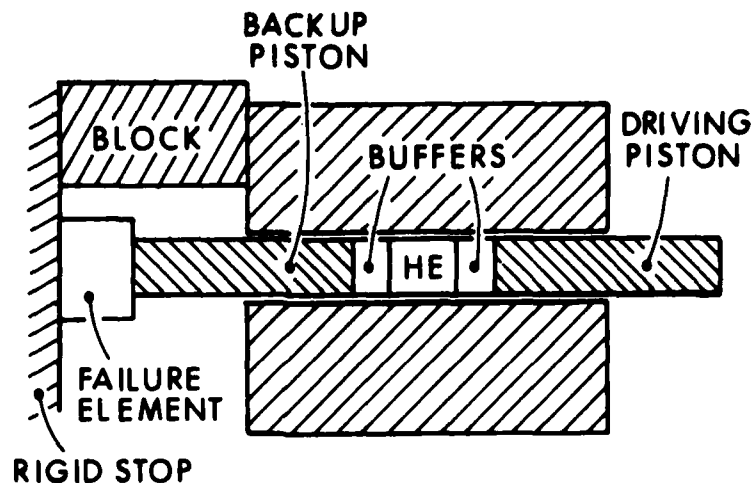


Figure 10. Friction Test Configuration

over the steel confinement. A failure element between the backup piston and the rigid stop controls the sliding of the sample. As pressure builds up in the breech, it is transmitted to the stop through the explosive sample and the failure element. The failure element is designed to yield when the pressure reaches a critical value. The explosive then slides with respect to the steel confinement at the elevated pressure set by the failure element. The confinement cylinder is kept from sliding by the block between it and the rigid stop. Not shown in the schematic is a block between the large piston and the rear stop to limit the slide to 12.7 mm. The activator can be instrumented to measure the sliding velocity directly but this was not done for these tests. The velocities in our experiments were less than 5 m/s. This is low compared to the estimated sliding velocity which may occur during launch. It is possible to obtain higher sliding velocities. A limitation of this configuration is that the state of stress varies from one end of the sample to the other because of the friction with the wall. This difficulty can be reduced by making the length of the sample as small as possible.

3. Results

Careful attention must be paid to the buffer material which is used between the steel pistons and the explosive sample. To find suitable materials, the substances listed in Table XIV were tested. As expected, lead, aluminum, and steel caused ignition. Those plastic materials that caused ignition had higher crystal melting temperatures or softening temperatures than those that did not cause ignition. Ignition was obtained with Cerrobend. The supposition is that the melting point is elevated under the conditions of the experiment.

Table XIV. Buffer Materials

Material	Melting or Softening Point ($^{\circ}\text{C}$)	Ignition
Polyethylene	40-50	No
Cerrobend	70.0	Yes
Polystyrene	66-91	No
Plexiglas	66-99	No
Teflon	121	Yes
Lexan	135-145	Yes
Lead	327.5	Yes
Aluminum	660.2	Yes
Steel	<1538.9	Yes

Both polyethylene and plexiglas buffers were used in the friction tests. The explosive was caused to slide over various steel surfaces with and without the standard primer paint. The results are presented in Table XV. No ignition was obtained in any case. The major surprise was that no ignition occurred when the explosive slid over a coating of the primer paint on rough steel. No effort was made to insure that the paint contained the maximum amount of large size grit permitted by the specifications. Future tests using such paint are planned.

Table XV. Friction Test Results

Steel Surface	Paint	Pressure (GPa)	Ignition Statistics
Smooth	No	0.19	0/1
Smooth	No	0.24	0/1
Smooth	No	0.42	0/1
Grooved	No	0.45	0/1
Rough	No	0.27	0/1
Rough	No	0.45-0.47	0/5
Grooved	Yes	0.19	0/1
Grooved	Yes	0.42	0/1
Rough	Yes	0.37	0/1
Rough	Yes	0.45	0/1

Several shots were fired in which sand particles of 0.7- to 1-mm diameter were present. These are summarized in Table XVI. A thin side cut was taken from the explosive sample and the space was packed with sand. This resulted in ignition. With one grain of sand in the side cut, no ignition occurred, but there was no guarantee that the sand remained in contact with the steel. When five grains of sand were placed individually in cavities naturally occurring on the surface of the explosive, no ignition resulted. However, when six grains of sand were imbedded in separate holes, which had been drilled to accommodate them on the cylindrical surface of the explosive sample, ignition

occurred upon testing. These two tests were performed to verify that ignition could have occurred in the XM650 projectile if such grit particles had been on the steel surface when the shell body rotated with respect to the fill.

Table XVI. Friction Test With Sand

Configuration	Number of Grains	Steel Surface	Pressure (GPa)	Ignition Statistics
Sand in Side Cut	Packed	Rough	0.37	1/1
Sand in Side Cut	1	-	0.37	0/1
Sand in Natural Cavities	5	Rough	0.36	0/1
Sand in Drilled Cavities	6	Smooth	0.37	1/1
Sand in Drilled Cavities	6	Smooth	0.23	1/1

4. Conclusions

In discussing the XM650 premature, we noted that if grit particles were present at the sliding interface then ignition could occur. In the light of the results with primer paint and sand, this conclusion should be amended to state that ignition will occur if there are sufficiently large grit particles present. The size required depends on the pressure and sliding velocity. In the present case, the sliding velocities were low. However, ignition with primer paint grit may occur at the higher sliding velocities that can occur during the launch of a projectile.

IV. CONCLUSIONS, SPECULATIONS, AND RECOMMENDATIONS

A. Compression

The activator experiments reported herein show conclusively that compression alone on a setback or impact time scale does not ignite composition-B. We know, however, that such ignitions are possible when the pressurization rate is high enough. The lowest pressurization rate that will cause ignition is as yet undetermined.

B. Compressive Heating

1. Role of Air and Pressurization Rate

The tests show that when a gap is present adjacent to the explosive sample the ignition response depends upon the amount of air in the gap (gap thickness and initial pressure), the pressurization rate and peak pressure, and the insulating capacity of the piston material. It is clearly established that the observed ignitions are due to the

presence of air since no ignitions occur under identical conditions in the absence of air in a gap. The role of pressurization rate and peak pressure is not clearly understood. These experiments were conducted in such a way that the pressurization rate and the peak pressure were increased in conjunction. The activator is not limited to operating in this manner and future tests are planned in which these parameters are varied independently. Our analysis¹⁰ shows that the peak temperature at the explosive-air interface usually occurs while the gap is still pressurizing and is a function of pressurization rate and not of peak pressure. On those occasions when the pressurization is terminated early at a low peak pressure, the peak temperature may be further limited and an ignition which would have otherwise occurred may be inhibited. Nevertheless, it appears that pressurization rate is the principal governing parameter.

2. Air Leakage

During gap closure, air leakage sufficient to grossly affect results appears to occur. This may be controlled, however, by precompressing the explosive and using shrink-fitted pistons or by using self-sealing gaps (such as the plastic bubbles) in which case precompression is not required. The sealed planar gap test and the bubble test represent appropriate procedures for testing explosives in the activator.

3. Explosive Surface Effects

It has been shown that precompressed samples are more sensitive to compressive heating ignitions than are unprecompressed samples and that as-cast surfaces are more sensitive than cut and polished surfaces, unless the latter have been precompressed. In order to clarify this, it is necessary to consider the role of surface defects. Past speculation has been that surface irregularities caused a greater explosive surface area to be exposed to the same volume of heated air and thus reduced sensitivity. However, the analysis indicates that the final gap thickness is of about the same magnitude as the surface irregularity ($\sim 10\mu\text{m}$), and contact between the explosive and the piston occurs, forcing air into the defects so that it does not contact a large-explosive surface. There are at least three ways in which an irregular surface can lead to the generation of hot spots and increase sensitivity. One is by the convergent flow of air into a defect. This has already been shown to have a sensitizing effect. Another way is the exposure of RDX particles in defects (or on a cut and polished surface). These do not appear on a perfectly cast surface. A third way in which high local temperatures may be achieved is by the concentration of energy in small protrusions or loose particles at the surface. These reach significantly higher temperature than the effectively semi-infinite planar explosive layers when exposed to hot gas at the same temperature. These three effects may act together to produce ignitions. A desensitizing effect may occur if the nature of the surface is such as to offer paths by which the compressing air may escape from the cavity. This provides a possible explanation for the high sensitivity observed for TNT.

4. Ignition Thresholds

The ignition threshold determined using the planar gap test is expressed in terms of critical values of base gap thickness and impact momentum. While use of the latter parameter reduces indeterminacy, it is not particularly useful since it does not indicate the important aspect of the stimulus, the pressurization rate. While this depends upon the impact momentum, it is also strongly affected by the mechanical properties of the explosive, buffer(s), and pistons, as well as their geometry. The pressurization rate delivered in the planar gap test is not the same as that delivered in the bubble test with the same impact momentum. Therefore, more meaningful and useful data may be obtained if the tests are conducted using pressure gages behind the sample, as in Figure 3. This is the procedure that we will use once a sufficient quantity of gages are available. Ignition thresholds may then be expressed in terms of pressurization rate and a parameter characterizing the gap.

C. Friction

We have shown that frictional heating ignitions are possible when sufficient large grit is present. The sliding velocities we obtained were low and no ignitions were caused by the grit in the standard primer paint. It is necessary to perform more experiments to determine if paint grit can cause ignition at higher sliding velocities. These are planned.

D. Implications for Ammunition Improvement

Several inferences which bear upon the issue of lowering the premature rate in fielded ammunition may be drawn from our results. The presence of a base separation provides an opportunity to create high pressurization rates and peak pressures when the explosive fill impacts the base of the projectile during launch. This is undesirable regardless of the active ignition mechanism(s). Compressive heating ignitions occur when the pressurization rate is sufficiently high, are associated with a base gap or defect near the base, and are enhanced by convergent geometries and explosive surface roughness. Any system which is proposed to eliminate base separations by bonding the fill to the shell wall must do so with absolute certainty. If gaps are present with bonded systems, the premature potential appears greater. These gaps will close at high acceleration when the bonding fails, leading to high pressurization rates. When the gaps are formed, they are more likely to produce rough surfaces in the interior of the fill near the base rather than the smoother cast surfaces at the base which occur in unbonded systems. Advantages might be obtained by creating conditions which promote leakage of air away from a local gap compression, either through the explosive surface or otherwise. We have also pointed out the danger of placing soft plastic materials in contact with the explosive particularly near the base of the projectile.

LIST OF SYMBOLS

D	diameter of large piston
M	mass of large piston
\dot{m}	air leakage rate
p	pressure
p_f	shear pin failure pressure
p_m	peak pressure
T	temperature
V	impact velocity
δ_F	free run
δ_g	gap thickness
δ_T	total run

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